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TECHNICOLOR LIMITS AT THE TEVATRON

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Direct searches for the technicolor particles at the Tevatron collider experiments at $\sqrt{s} = 1.8$ TeV are described. Various color-singlet and color-octet heavy technimeson states are predicted in the recent technicolor models. The topcolor assisted technicolor model predicts new heavy gluon, top-gluon. These new particles, ρ_T , ω_T , π_T , and top-gluon are expected to be produced in high energy $p\bar{p}$ collisions if they exist and they are searched in the world highest energy $p\bar{p}$ collider experiments, CDF and D0 experiments. In this report, current mass limits for these particles are shown.

1 Introduction

High energy particle experimental results have agreed very well with the Standard Model of elementary particles and fields. However, the origin of the electroweak symmetry breaking has not yet been explained experimentally. Although the higgs mechanism is one of the solution, the higgs particle has not yet been found. An alternative explanation for the broken symmetry is the technicolor model¹. Technicolor is a strong interaction of new technifermions and gauge bosons at a scale of $\Lambda \sim 1$ TeV. In the technicolor model, the higgs boson is replaced by the technipions ($\pi_T^{0\pm}$) which are the states of two techniquarks bounded by the technicolor force. Fermion masses are generated by the extended technicolor gauge bosons².

In the walking technicolor model⁴, color-singlet technimesons can exist with relatively lower mass than 1 TeV. In high energy $p\bar{p}$ collisions, color-singlet technirhos ($\rho_T^{0\pm}$) and techniomega (ω_T^0) are produced through the s -channel virtual W, Z, γ bosons. The decay modes of the technirhos are $\rho_T^\pm \rightarrow W^\pm \pi_T^0, Z^0 \pi_T^\pm, W^\pm Z^0, \pi_T^0 \pi_T^\pm$, and a fermion pair ($f\bar{f}'$), and $\rho_T^0 \rightarrow W^\pm \pi_T^\mp, W^\pm W^\mp, \pi_T^\pm \pi_T^\mp$, and $f\bar{f}$. The dominant decay modes of techniomega are $\omega_T^\pm \rightarrow \gamma \pi_T^0, Z^0 \pi_T^0$. Search for color-singlet technirho, technipion, and techniomega are described in the section 2 to 5.

The color-octet technirho is produced through the s -channel gluon in $p\bar{p}$ collisions. A narrow resonance is searched in the dijet and $b\bar{b}$ mass spectra for finding the color-octet technirho. A wide resonance is searched in the $b\bar{b}$ mass spectrum for finding the top-gluon. The top-gluon is a color-octet gauge bosons predicted from the topcolor assisted technicolor. Search for color-octet heavy new particles are described in the section 6. Some examples of the feynman diagrams of our searched processes are shown in figure 1.

2 Technirho and Technipion Search : Leptonic Mode

The technirho and technipion search using leptonically decayed W and two heavy quark jets final states in 109pb^{-1} of the CDF data is described in this section⁵.

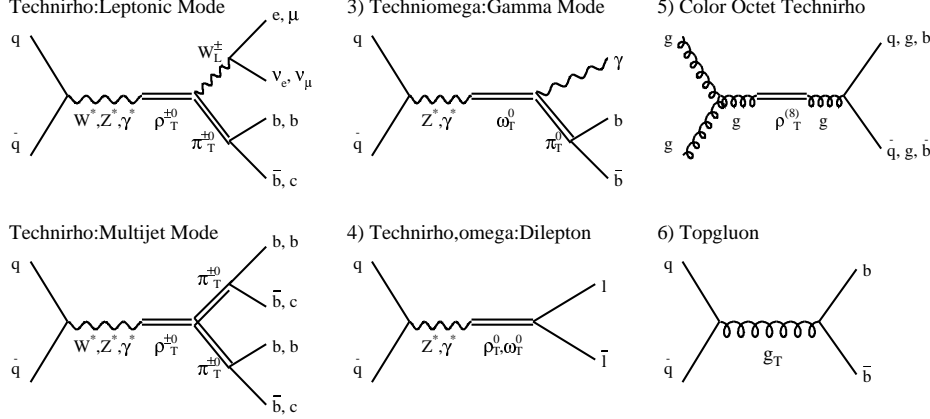


Figure 1. Feynman diagrams of the technicolor production for our searched processes are shown. Leptonic decay mode and multijet decay mode of the color-singlet technirho production diagrams are shown in 1) and 2). The techniomega production diagram is shown in 3). Dilepton decay mode of the technirho and techniomega is shown in 4). Dijet and $b\bar{b}$ decay mode of color-octet technirho is shown in 5). The $b\bar{b}$ decay mode of the top-gluon is shown in 6).

The search modes are $\rho_T^{0\pm} \rightarrow W^\pm \pi_T^{0\pm} \rightarrow \ell \nu b\bar{b}(b\bar{c})$, where the ℓ represents electron or muon. Technipions decay mostly ($\sim 90\%$) to $b\bar{b}$ or $b\bar{c}$. The branching ratio of the technirho depends on $M(\rho_T)$ and $M(\pi_T)$. For masses $M(\pi_T) = 90 \text{ GeV}/c^2$ and $M(\rho_T) = 180 \text{ GeV}/c^2$, $\rho_T \rightarrow W\pi_T$ is the dominant decay mode and the cross section is large enough in this mode that we might observe using current data at the Tevatron, $\sim 15 \text{ pb}$ ⁶.

A counting experiment has been done for this mode. We search for a technipion mass resonance in the invariant mass distribution of the b -tagged two jets system and a technirho mass resonance in the invariant mass distribution of the W and b -tagged two jets system. In the data selection, we require either an isolated electron with $E_T > 20 \text{ GeV}$ or an isolated muon with $P_T > 20 \text{ GeV}/c$ in the central region, $|\eta| < 1.0$. We also require the missing transverse energy, $\cancel{E}_T > 20 \text{ GeV}$, and exactly two jets with $E_T > 15 \text{ GeV}$ and $|\eta| < 2.0$ with a fixed cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. After the $W + 2\text{jet}$ selection, we require that at least one of the jets be identified as a b -jet using SVX silicon microstrip vertex detector by finding the secondary decay vertex of the B meson (SVX b -tag). The observed number of events is 42 , while the expected number of background events is $31.6 \pm 4.3(\text{syst.})$ giving the significance of the excess about 1.5σ . To get larger sensitivity, additional mass dependent selection criteria are applied on the ϕ angle between the two jets, $\Delta\phi(jj)$, and the P_T of the dijet system, $P_T(jj)$, (topology cuts). Since the technipion is produced nearly at rest on the transverse plane of the beam axis in our search mass region, the $P_T(jj)$ is smaller and the $\Delta\phi(jj)$ is more back-to-back than the background expected. The $P_T(jj)$ and the $\Delta\phi(jj)$ distributions of the technicolor signal, the background expected, and the cut values are shown in figure 2 (*left*). The dijet mass and the W and two jets mass distributions of the CDF data, background expected, and predicted technicolor signal plus background before and after topology cuts are shown in figure 2 (*right*). Finally,

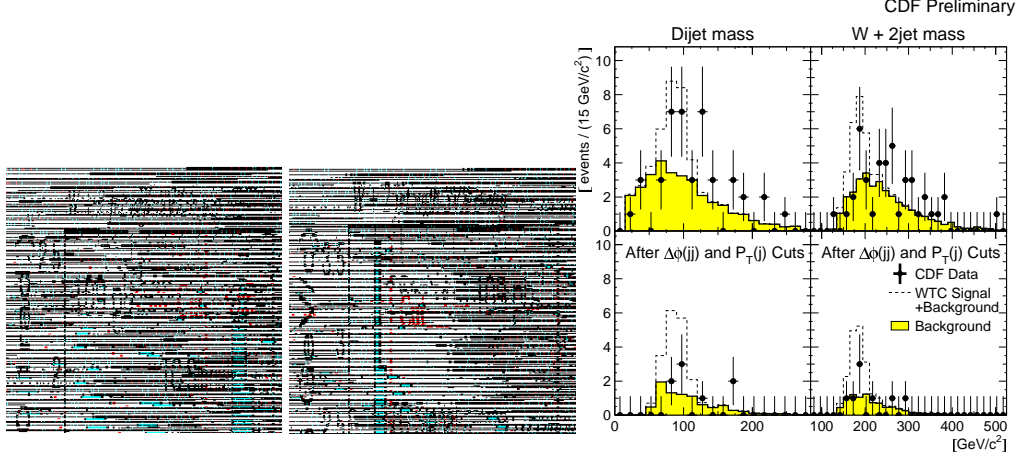


Figure 2. *Left* : Dijet opening angle on the r - ϕ plane and the P_T of the dijet system of the W +2jet with b -tagged selected sample of the technicolor signal and the background expected. Topology cut values are shown as a vertical dashed line. The mass combination is $M(\pi_T) = 90 \text{ GeV}/c^2$ and $M(\rho_T) = 180 \text{ GeV}/c^2$. *Right* : Invariant mass of the dijet system and the W +2jet system in the W +2jet with single SVX b -tagged CDF data are shown. Requirements of $\Delta\phi(jj) > 2.1$ and $P_T(jj) < 40 \text{ GeV}/c$ are applied in the bottom plots. Expected technicolor signal and the background are shown in the same plots.

mass window cuts within 3σ of the technicolor signal are applied on the dijet and the W and two jets mass distributions. After all the selection criteria, 5 events remained in the CDF data while the expected number of background events is 5.7 at a mass combination of $M(\pi_T) = 90 \text{ GeV}/c^2$ and $M(\rho_T) = 180 \text{ GeV}/c^2$. Since no excess is seen in any other mass combinations we examined, we set 95% C.L. upper limits for the production cross section and set an excluded region on the $M(\rho_T)$ versus $M(\pi_T)$ plane. The excluded region is shown in figure 3 (*left*).

3 Technirho and Technipion Search: Multijet Mode

For the mass region of $M(\pi_T) < \frac{1}{2}M(\rho_T)$, the $\rho_T \rightarrow \pi_T\pi_T$ decay dominates. This gives $b\bar{b}b\bar{b}$ or $b\bar{b}b\bar{c}$ final states. Other decay modes, $\rho_T \rightarrow W\pi_T, Z\pi_T$ also produce the multijet final states with at least two heavy quarks. Search for technirhos and technipions in heavy quark rich multijet final states using 91 pb^{-1} of the CDF data is described in this section.

The event selection criterion is basically same as the Standard Model higgs search in the multijet final state at the CDF⁷. Events are required to have four or more jets with uncorrected $E_T > 15 \text{ GeV}$ and $|\eta| < 2.1$. We also require that at least two among the four highest E_T jets in the event are identified as b quark candidates using the SVX b -tagging. The two highest E_T b -tagged jets are assigned to the technipion, and the other two to the vector boson or the other technipion. An additional requirement, $\Delta\phi(b\bar{b}) \geq 1.5$ is applied to remove the gluon splitting component of the QCD background and to reduce the wrong jet assignments of the technipion.

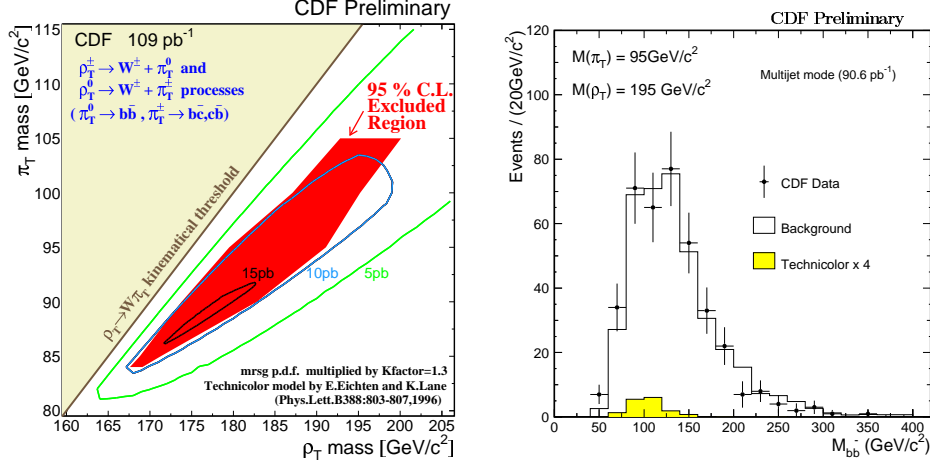


Figure 3. *Left* : The shaded region shows 95% C.L. excluded region in the $M(\pi_T)$, $M(\rho_T)$ plane extracted from the leptonic mode technirho and techninipion search analysis at CDF. Three contours of the theoretical production cross section are shown on the same plane. *Right* : The $b\bar{b}$ mass distribution from the double b -tagged multijet mode analysis. The number of background is normalized to data, and the number of technicolor signal is normalized to the expected number of events times 4 in 90.6^{-1} .

We observe 389 events in the CDF data. Figure 3 (*right*) shows an invariant mass distribution of the b -tagged dijet system for data, background, and a technicolor signal at $M(\pi_T) = 95 \text{ GeV}/c^2$ and $M(\rho_T) = 195 \text{ GeV}/c^2$. A binned maximum-likelihood fitting process on the $b\bar{b}$ mass distribution is repeated for various $M(\rho_T)$ and $M(\pi_T)$ combinations. The QCD, $t\bar{t}$, $Z(\rightarrow b\bar{b}, c\bar{c})$ +jets, mistag background, and the technicolor signal distribution are fitted to the data. The QCD and signal normalizations are left free in the fit while the other backgrounds are constrained around their expected number of events within their uncertainties. The fits give us the results with very small technicolor signal contribution for any mass combinations in our search region. Then the 95% C.L. cross section upper limits are set on the multijet final states of the technirho productions. The cross section upper limits are about 50 times greater than the theoretical cross sections in any mass combinations we examined. For an mass combination of $M(\pi_T) = 95 \text{ GeV}/c^2$ and $M(\rho_T) = 195 \text{ GeV}/c^2$, the cross section upper limit is 613pb while the theoretical cross section is 12.3pb, where the mass combination is just outside of the already excluded region from the leptonic mode analysis.

4 Technirho and Techniomega Search : Dilepton Mode

Search for technirho and techniomega particles using the decay channel $\rho_T, \omega_T \rightarrow e^+e^-$ in the 120 pb^{-1} of the D0 data is described in this section. The isoscalar techniomega is nearly degenerate with technirho. The production cross section of the techniomega is sensitive to the charges of the technifermions and a mass parameter M_T . In this analysis, the technifermion charges are set to be $Q_U = \frac{4}{3}$

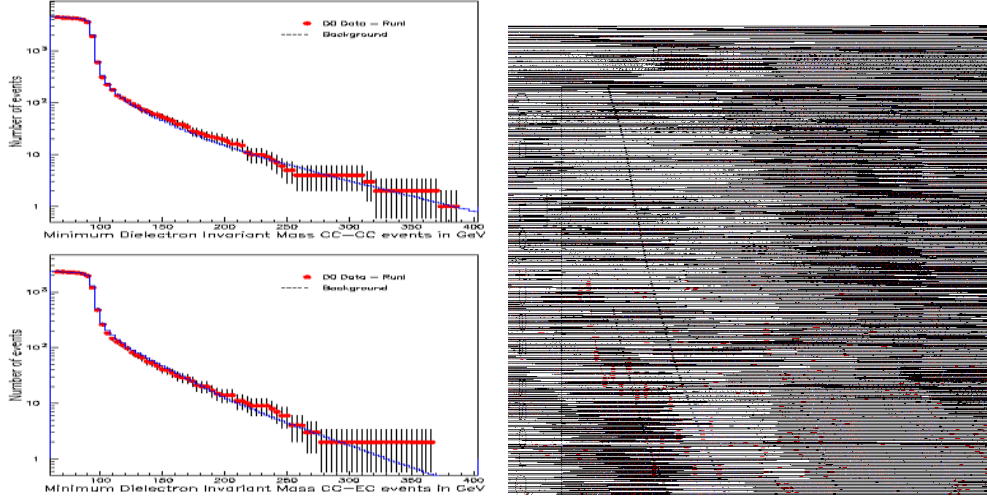


Figure 4. *Left* : The dielectron mass distribution of the CC-CC(top) and the CC-EC(bottom) events in the 120 pb^{-1} of the D0 data and the background are shown. Number of events are integrated from the highest event. No excess of the technirho and techniomega resonance is seen in the distribution. *Right* : The 95% C.L. cross section upper limits as a function of dielectron mass. Two theoretical cross sections are drawn in the same plot with $M(\rho_T, \omega_T) - M(\pi_T) = 60 \text{ GeV}/c^2$ and $100 \text{ GeV}/c^2$.

and $Q_D = Q_U - 1 = \frac{1}{3}$, and the M_T is expected to be several 100 GeV ⁶.

Events with two high E_T electrons are selected in the D0 data. Electron identification is defined with two categories: “tight” and “loose”. A tight electron satisfies the following criteria: the calorimeter cluster has high electromagnetic fraction ($> 95\%$); the cluster shape is consistent with that expected for an electron; the cluster is isolated from other calorimeter activity, and there is a good quality track matched with the cluster. The last criterion is not imposed for a loose electron. Selected electrons are categorized to the pseudorapidity region $|\eta| < 1.1$ for the Central Calorimeter (CC), and $1.5 < |\eta| < 2.5$ for the forward (End) Calorimeter (EC). Dielectron event selection requires either both electrons central (CC-CC), or one electron central and the other electron forward (CC-EC). Every event requires at least one tight electron, and second electron can be tight or loose. Both electrons are required to have $E_T > 25 \text{ GeV}$. The EC calorimeter electrons are always required to be tight.

The backgrounds in the dielectron events include two major components: 1) Drell Yan + Z background, 2) background due to misidentified electron from dijet events, W + jets events, and γ + jets events. Figure 4(*left*) shows the integrated plots of the dielectron mass distributions of the D0 data and the background expected for the CC-CC events and the CC-EC events. In the absence of a signal above background, a 95% C.L. upper limit is set on the cross section as a function of the dielectron invariant mass. The experimental limit obtained is shown as dots connected by a curve in figure 4(*right*). The theoretical predictions for the cross section for the process $\rho_T, \omega_T \rightarrow e^+e^-$ are also plotted in figure 4(*right*). In this plot, two theoretical predictions are shown vary in the mass difference between the ρ_T, ω_T , and π_T^\pm . For mass difference less than the mass of the W boson, the decay

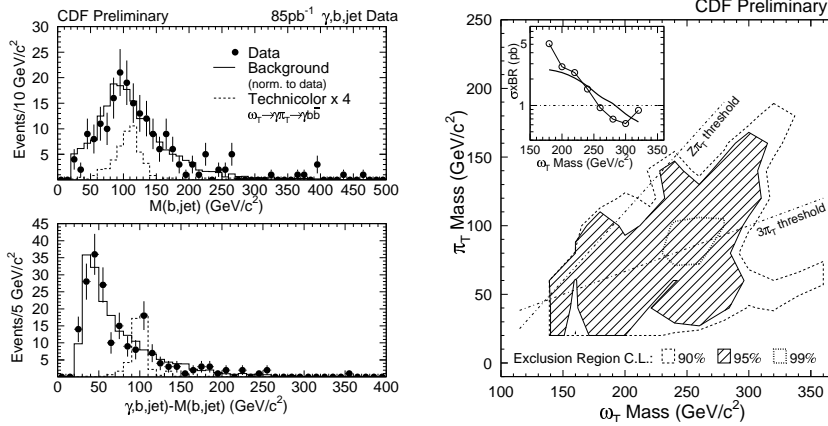


Figure 5. *Left* : The distributions of M_{jj} and $M_{jj\gamma} - M_{jj}$ for the CDF data, background, and expected technicolor signal times 4. *Right* : The 90%, 95%, and 99% C.L. excluded region on the M_{jj} versus $M_{jj\gamma}$ plane for the $\omega_T \rightarrow \gamma\pi_T \rightarrow b\bar{b}\gamma$ mode search at CDF.

$\rho_T \rightarrow W + \pi_T$ is forbidden and the cross section to dielectron is larger than that of in the mass difference of $100 \text{ GeV}/c^2$, where the $W\pi_T$ decay mode is allowed. In this analysis, we rule out ρ_T and ω_T with masses below $225 \text{ GeV}/c^2$, for a mass difference between ρ_T and π_T is smaller than the W boson.

5 Techniomega Search: $\omega_T \rightarrow \pi_T\gamma$ Mode

Search for techniomega (ω_T) particle using 85 pb^{-1} of the CDF data is described in this section⁸. If the techniomega exists, a likely decay mode is $\omega_T \rightarrow \gamma\pi_T$, followed by $\pi_T \rightarrow b\bar{b}$, the resulting signature is $\gamma b\bar{b}$ ⁶.

Event selection requirements are an isolated central electromagnetic cluster with $E_T > 25 \text{ GeV}$ and $|\eta| < 1.0$, at least two jets with each jet having corrected $E_T > 30 \text{ GeV}$ and $|\eta| < 2.0$, and one of the jets to be identified as a b -quark jet by the SVX b -tagging. The 200 events survived in the CDF data by the event selection. Three source of backgrounds are expected from the Standard Model processes; events with jets misidentified as photons, events with photon and mis-tagged jets, and events with standard model production of photon with heavy flavor quarks. The total background is estimated to be $131 \pm 30 \pm 29$ events. The 200 events in the data sample do not constitute a significant excess over standard model expectations.

Two invariant masses are calculated, mass of the tagged jet and the highest E_T untagged jet, M_{jj} , corresponding to the π_T mass, and mass of the two jets plus the photon, $M_{jj\gamma}$, corresponding to the ω_T mass. The distributions of M_{jj} and $M_{jj\gamma} - M_{jj}$ for the data, background, and expected technicolor signal are shown in figure 5 (*left*). The mass difference, $M_{jj\gamma} - M_{jj}$, is used because the signal would appear with a good resolution by the cancellation of the jet energy resolution uncertainty. Fits are performed in the mass difference distributions for various techniomega and technipion mass combinations. The fit results give at most 2.2σ excess in all the mass combinations in this analysis. The cross section upper limits are set in various $M(\omega_T)$ and $M(\pi_T)$ mass combinations and set an excluded region on the $M(\omega_T)$ versus $M(\pi_T)$ plane as shown in figure 5 (*right*).

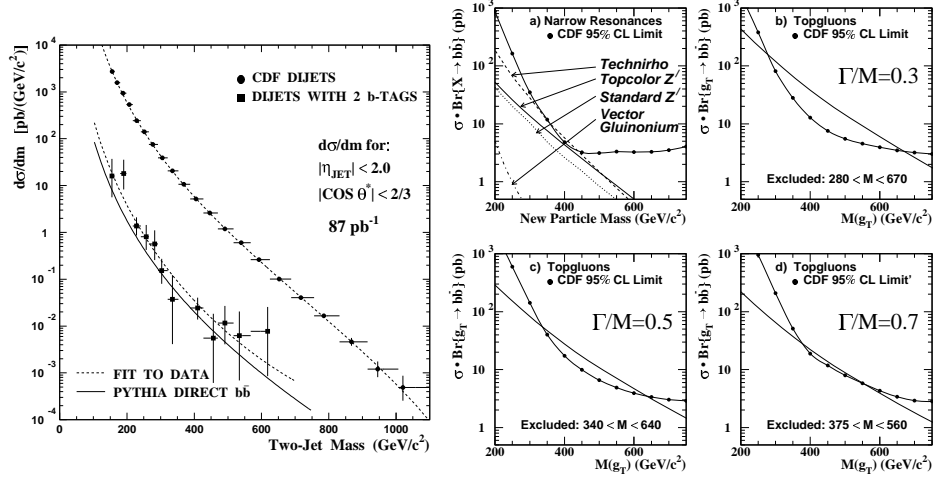


Figure 6. *Left* : The dijet mass (top) and double- b -tagged dijet mass (bottom) distributions compared to a fit to a smooth parameterization (curves) and to the PYTHIA prediction. *Right* : The 95% C.L. upper limit on the cross section times branching ratio (dots), for narrow resonances and top-gluons of width $\Gamma = 0.3M$, $\Gamma = 0.5M$, and $\Gamma = 0.7M$, are compared to theoretical predictions (curves).

6 Color-octet Technirho and Top-gluon

Search for narrow resonance of the color-octet technirho and a wide resonance of the top-gluon in the $b\bar{b}$ and dijet mass spectra are described in this section⁹. The 87 pb^{-1} of the CDF data is used in this analysis. The top-gluon is predicted in topcolor assisted technicolor which accommodates the heavy top quark mass³. The top-gluon is expected to have a large width, so we search for three different widths, $\Gamma = 0.3M, 0.5M$, and $0.7M$, where the M is the new particle's mass. For narrow resonances we consider color-octet technirhos from a model of walking technicolor⁴.

Events are selected requiring two or more jets where the two leading jets have $|\eta| < 2$ and a scattering angle in the dijet center-of-mass frame $|\cos \theta^*| = |\tanh[(\eta_1 - \eta_2)/2]| < 2/3$. The $\cos \theta^*$ requirement reduces the QCD background which peaks at $|\cos \theta^*| = 1$. Backgrounds from cosmic rays, beam halo, and detector noise were removed. We use tracks reconstructed using the SVX detector to identify secondary vertices displaced from the event vertex. Both jets are required to be tagged. The efficiency for b -tagging a heavy object decaying to $b\bar{b}$ decreases from 11% to 2.5% as the dijet mass increases from 200 to $650 \text{ GeV}/c^2$. In figure 6(*left*), the inclusive dijet mass distribution for untagged and double- b -tagged dijet distributions are shown. The data are compared to a smooth parameterization and the PYTHIA prediction of the $b\bar{b}$ events. In the absence of evidence for new physics, we proceeded to set upper limits on the cross section for new particles. Figure 6(*right*) shows the measured upper limits on the cross section times branching fraction as a function of new particles mass. For narrow resonances we exclude the color-octet technirho in the mass interval $350 < M < 440 \text{ GeV}/c^2$. We exclude top-gluons of width $\Gamma = 0.3M$ in the mass range $280 < M < 670 \text{ GeV}/c^2$, of width $\Gamma = 0.5M$ in the mass range $340 < M < 640 \text{ GeV}/c^2$, and of width

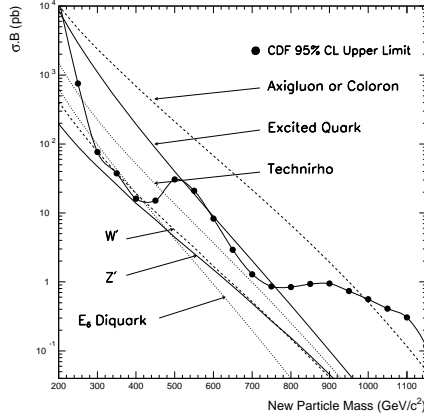


Figure 7. Cross section upper limits and the theoretical cross section for various new particles as a function of the dijet mass. We excluded the color-octet technirho in the region of $260 \text{ GeV}/c^2 < 470 \text{ GeV}/c^2$ from the dijet mode analysis in 106 pb^{-1} of the CDF data.

$\Gamma = 0.7M$ in the mass range $375 < M < 560 \text{ GeV}/c^2$. Figure 7 compares the cross section upper limit measured from the untagged dijet mass spectrum to the theoretical cross section for various new particles as a function of dijet mass¹⁰. The excluded region of the color-octet technirho from the dijet mode analysis is set in $260 \text{ GeV}/c^2 < M_{\rho_T^8} < 470 \text{ GeV}/c^2$.

7 Summary

We have searched color-singlet and color-octet technicolor particles and top-gluons in $p\bar{p}$ collisions at the Tevatron experiment at $\sqrt{s} = 1.8 \text{ TeV}$. In conclusion, no evidence has been seen in any signatures we searched for at the CDF and D0 experiments using RUN-I data obtained in 1992-1996. We set cross section upper limits and exclude some region on the technicolor mass parameter spaces. Throughout the analysis, secondary vertex tagging is a very powerful method for detecting the technicolor signal with heavy quark rich final states. In RUN-II at the Tevatron, high performance silicon vertex detector will be installed in both of the Tevatron collider experiments. In addition to more than twenty times increasing of the integrated luminosity, by the significant detector upgrading, the RUN-II experiment would be exciting for technicolor particles search.

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